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Reliability, Maintainability, and Availability –Consideration during the Design Phase in Ground Systems to Ensure Successful Launch Support

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Reliability, Maintainability, and Availability:

***Consideration During the Design Phase in
Ground Systems to Ensure Successful
Launch Support***

**Space Congress – “A New Beginning”
Friday, December 7, 2012
10:00 am**

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What is GSDO?

- **Ground Systems Development and Operations (GSDO) Program**
 - 1 of 3 NASA Programs based at Kennedy Space Center (KSC)
 - Established to develop and use the complex equipment required to safely handle rockets and spacecraft during assembly, transport, and launch
- **The GSDO Program Vision**
 - Launching the world's most powerful, advanced launch vehicles and spacecraft.
- **The GSDO Program Mission**
 - To be the driving force that transforms the Kennedy Space Center into the world's premier multi-user launch and landing spaceport.



What is RMA?

- RMA is the acronym for Reliability, Maintainability, and Availability
 - Reliability (R)
 - *The probability (likelihood) that a component or system will perform its intended function with no failures for a given period of time (mission time) when used under specific operating conditions (test environment or operating environment)*
 - Maintainability (M)
 - *The probability a failed item will be restored or repaired to a specified condition within a given period of time*
 - Availability (A)
 - *The probability that a repairable system will perform its intended function at a given point in time or over a specified period of time when operated and maintained in a prescribed manner. Thus , availability is a function of reliability and maintainability*
- If “R” is enough, then no need for “M” to achieve “A”; if “R” is not enough, then “M” is needed to achieve “A”

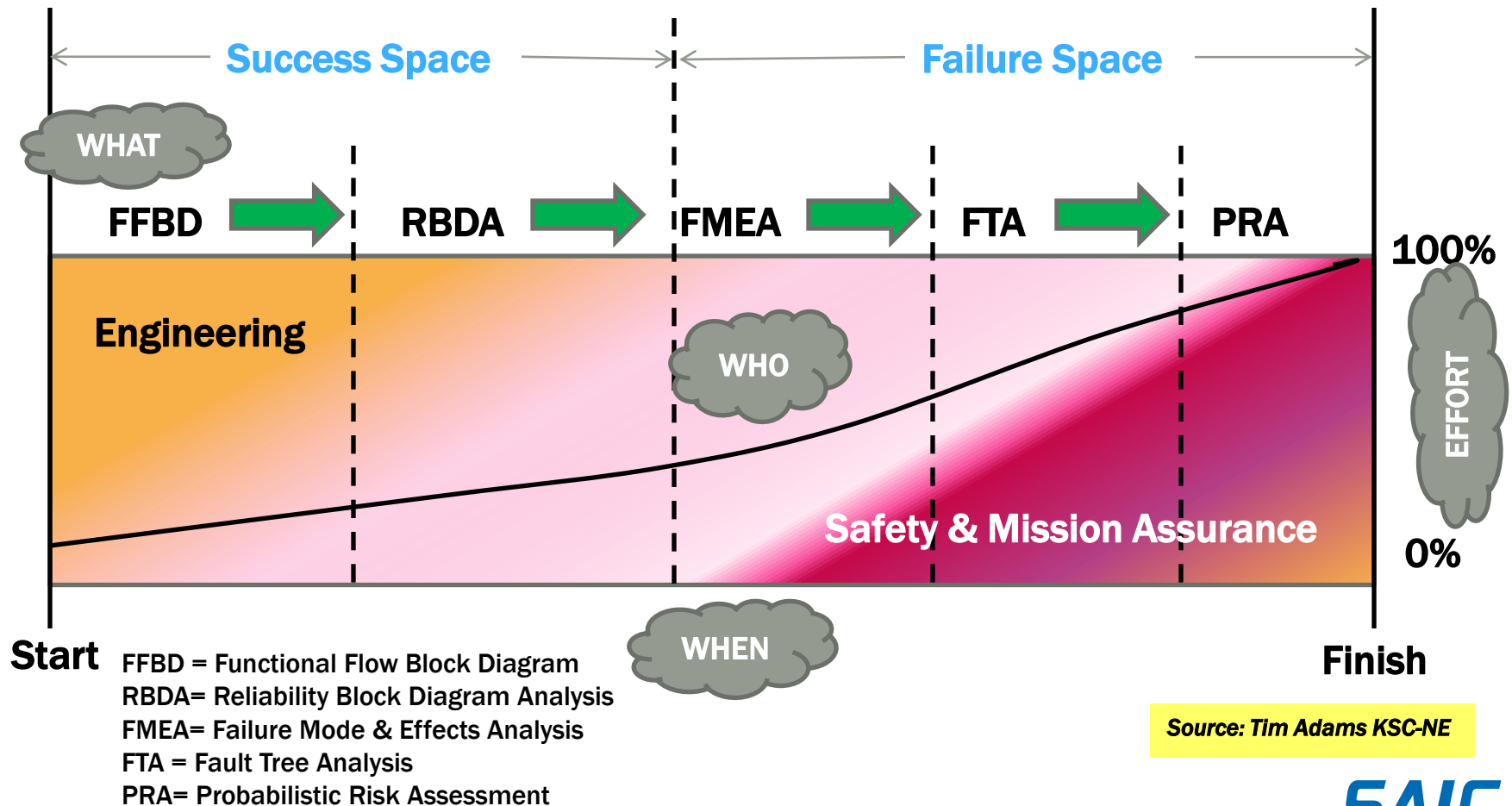
$$f(R,M) = A$$

RMA Analysis Purpose

- To reduce lifecycle cost by:
 - *Efficiently and effectively identifying limitations within a system that may cause a failure before the intended lifetime*
 - *Identify unreliable systems that may pose a safety or health hazard*
 - *Providing specific reliability requirements for component procurement*
 - *To identify wasted efforts and hardware that were intended to improve Availability, but are providing little value*
- To study, characterize, measure, and analyze the failure and repair of systems in order to:
 - *Improve their operational use by increasing their design life*
 - *Eliminate or reduce the likelihood of failures and safety risks*
 - *Reduce downtime (maintenance), thereby increasing available operating time*

RMA Design Life Analysis Process

- Ideally, the Reliability Engineering process looks like this:

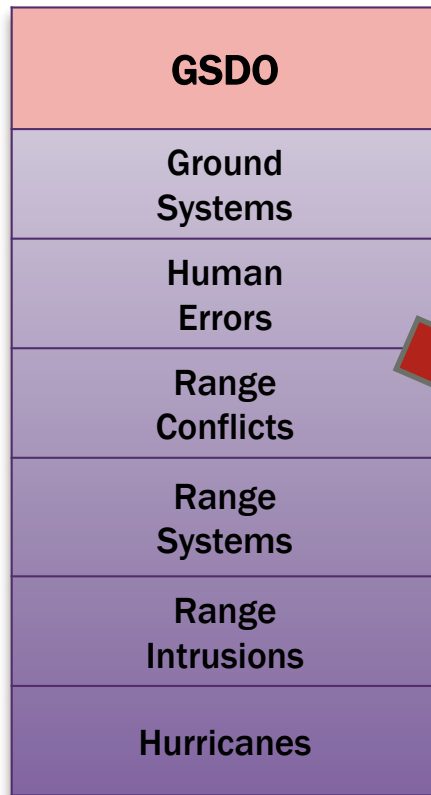


GSDO RMA: Solution to a Challenge

- **GSDO Program needs to deliver high launch probability**
 - Lunar missions and beyond require multiple launches and payloads to achieve mission goals
 - Commercial, DoD, and NASA customers will desire high availability from Ground Systems for launch support
 - The cost of each launch "scrub" is severe
 - De-tanking vehicles, re-synchronizing orbits, rescheduling Range conflicts, resting crew, etc
 - If a ground systems cause this scrub (*when the vehicle was otherwise "Available"*), then the community's penalty is even more severe
- **High Probability of Successful launch is needed; however, challenges were faced:**
 - KSC Ground Systems delivered 88% probability of launch during Space Shuttle Program (SSP) for any given launch countdown
 - KSC Ground Systems Constellation Program (CxP) requirement was 99% probability of launch for the last 10 hours of launch countdown
 - GSDO Program requirement is 98% Inherent Launch Availability for any given launch countdown

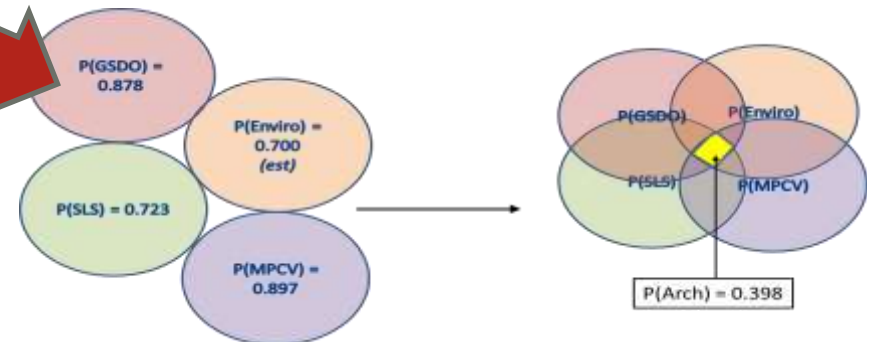
GSDO RMA: Solution to a Challenge

- Risk Factors for GSDO:



- Risks for launch probability:

- GSDO
- Space Launch System (SLS) – the Launch Vehicle
- Orion Multi-Purpose Crewed Vehicle (MPCV)
- Environments – Launch Weather (Wx), Abort Wx, Sea State



Example of Probability of Architecture on Any Given Launch Attempt*

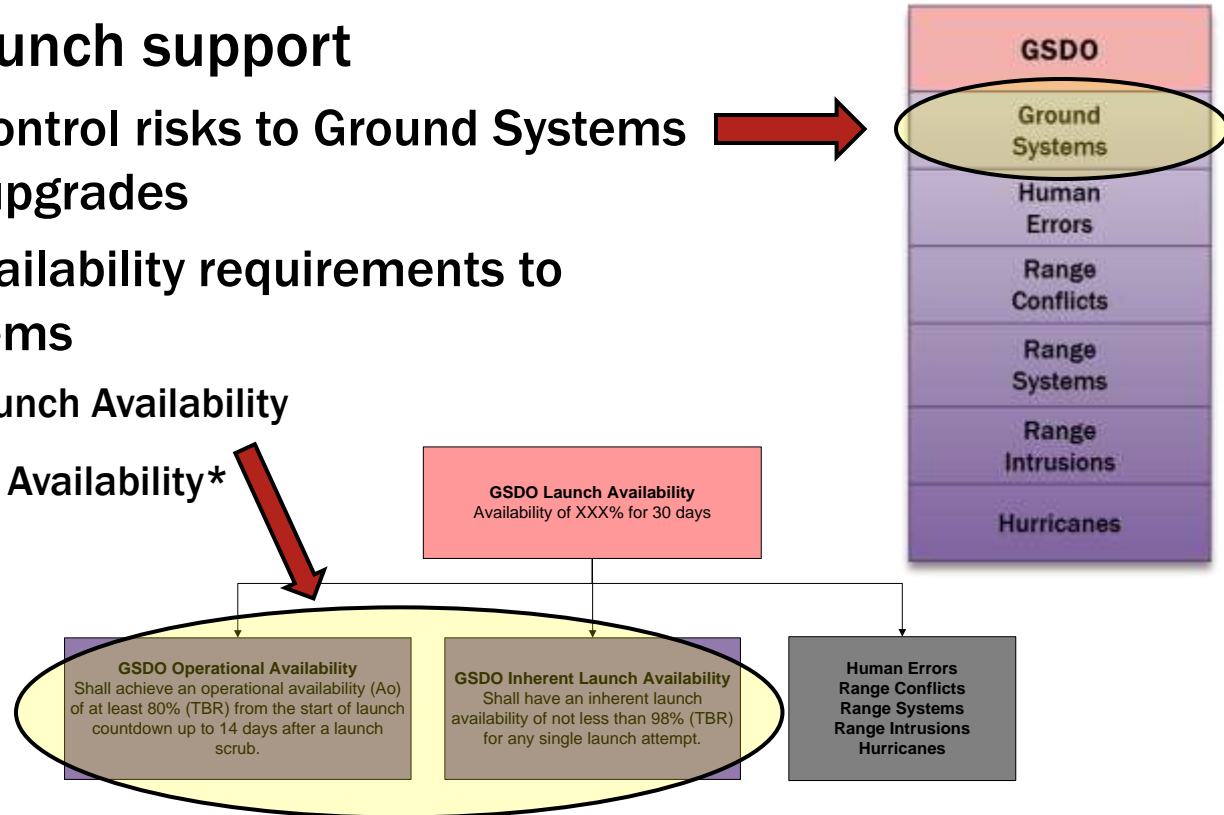
**Does not necessarily represent actual risk probabilities.*

GSDO RMA: Requirement Development

- Needed to put requirements in place to minimize risks to successful launch support

- Only could control risks to Ground Systems design and upgrades
- Allocated Availability requirements to ground systems

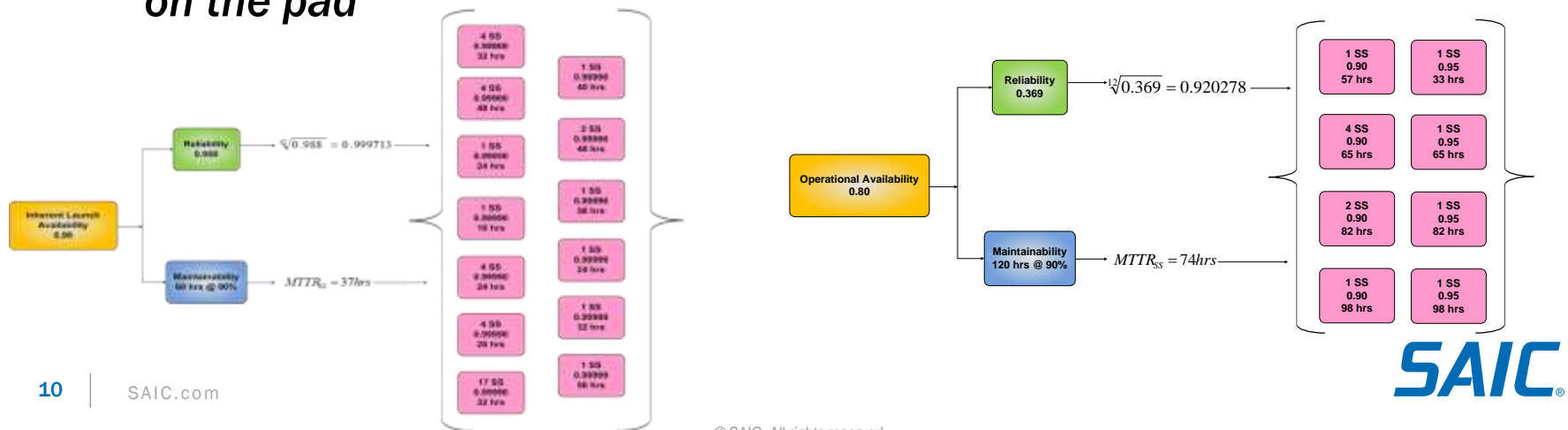
- Inherent Launch Availability
- Operational Availability*



**The Operational Availability requirement is not the classical Operational Availability (A_o) calculation. It is allocated as Inherent Availability (A_i). From a system design point of view, the A_i is of more interest than A_o because spares and repair capability involve resources and trade-offs external to the system design.*

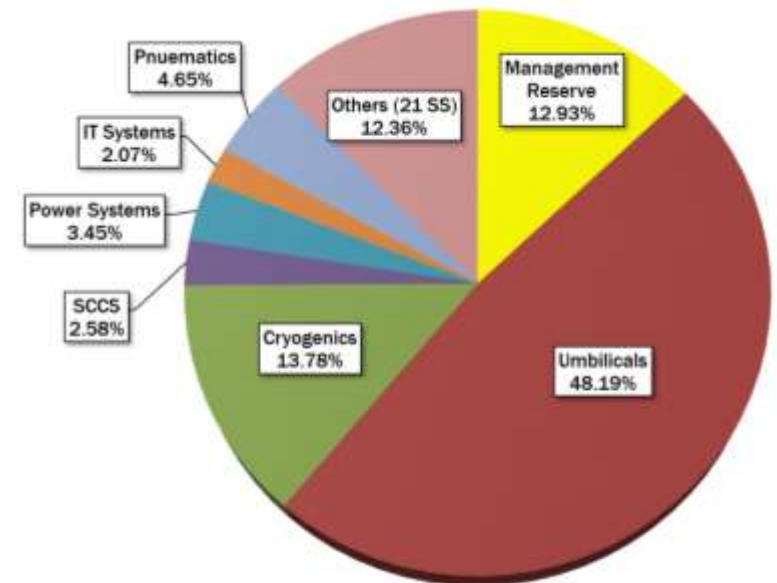
GSDO RMA: Requirement Allocation

- Reliability allocations made via improved Reliability Apportionment Method
 - Accounts for knowledge of ground system performance, design, and use*
- Maintainability allocations made via an improved MIL-HDBK-417A method
 - Accounts for knowledge of ground system design, fault isolation techniques, and maintenance design characteristics, i.e., accessibility on the pad*



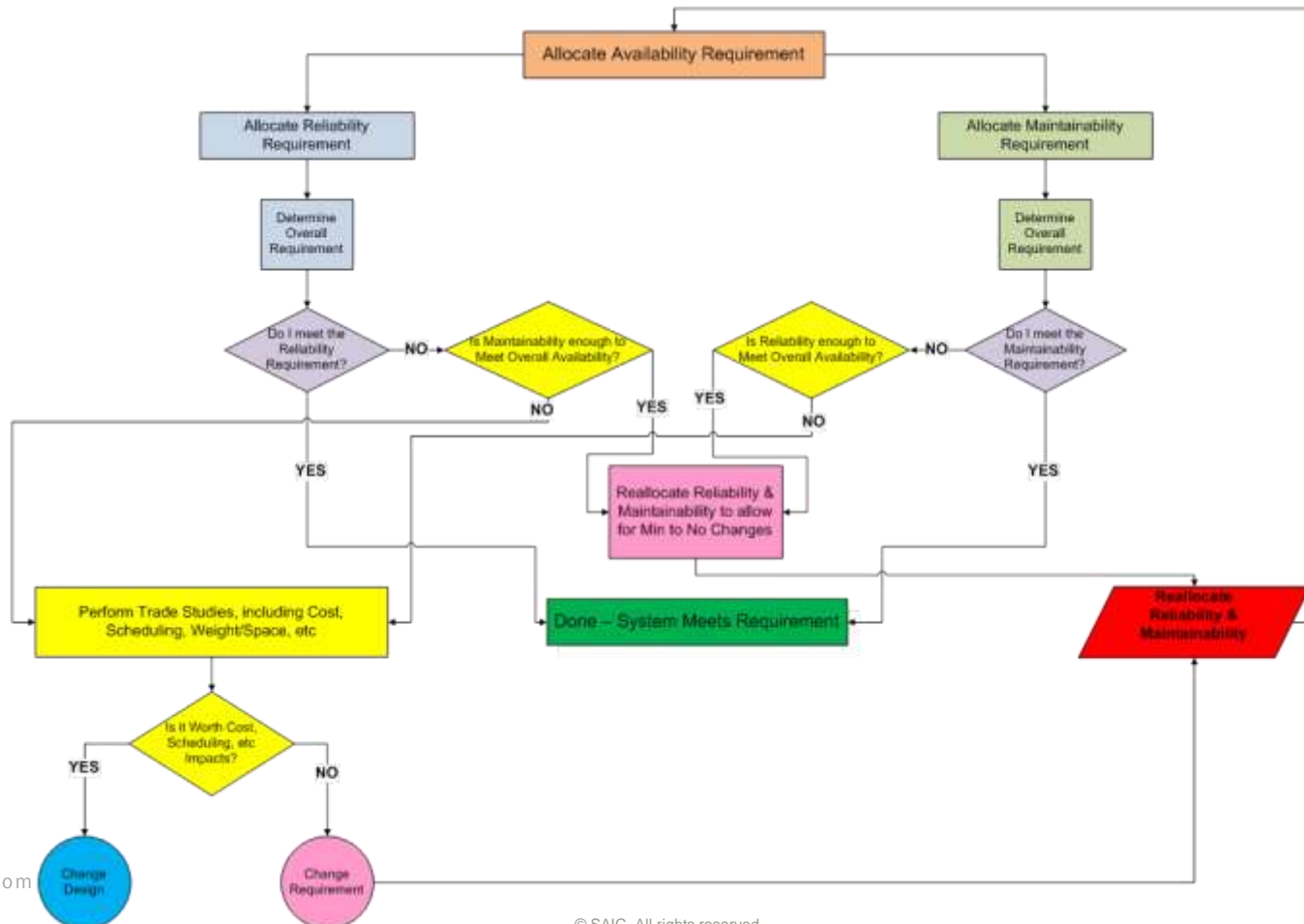
GSDO RMA: Requirement Allocation

- “Management reserve” is built into each RMA requirement allowing for room for growth in GSDO subsystems
 - Fraction of the overall requirement is unallocated
 - If the cost for an availability improvement in a subsystem design outweighs the benefit in increased GSDO launch availability, there is enough management reserve to leave the design as-is, in most cases
- The RMA analyses are completed during the design and upgrade schedules
 - RMA analysis is a required product for design milestones (30/60/90 or 45/90)
 - RMA analyses are performed as requested to assist in trade studies



GSDO RMA: Requirement Allocation

- Allocation is an iterative process
 - As designs are analyzed, allocations may need to be adjusted



RMA Analysis of GSDO Subsystems

1) Develop Component List from Subsystem Drawings

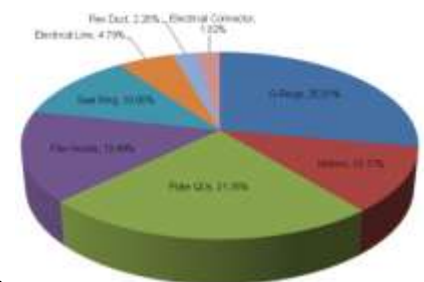
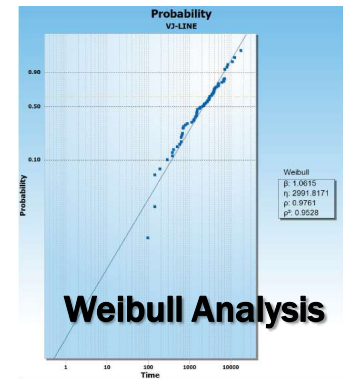
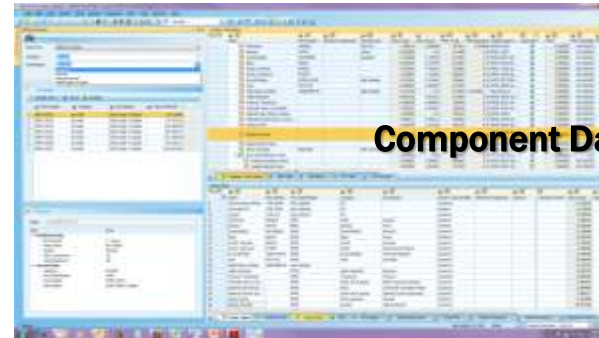
2) Develop Reliability Block Diagram (RBD) from Subsystem Drawings

3) Determine Reliability, Maintainability, and Availability from RBD

4) Determine Cut Sets from RBD

5) Determine Importance Measures from Cut Sets

6) Report Results and Recommendations in Subsystem RMA Reports



Cut Set	Reliability	Maintainability	Availability	Component Failure	Component Failure
1	0.999146	0.999146	0.999146	ACPU / Modem (Modem-1)	ACPU / Modem (Modem-1)
2	0.999146	0.999146	0.999146	ACPU / Modem (Modem-2)	ACPU / Modem (Modem-2)
3	0.999146	0.999146	0.999146	MODEM / Modem (Modem-3)	MODEM / Modem (Modem-3)
4	0.999146	0.999146	0.999146	MODEM / Modem (Modem-4)	MODEM / Modem (Modem-4)
5	0.999146	0.999146	0.999146	MODEM / Modem (Modem-5)	MODEM / Modem (Modem-5)
6	0.999146	0.999146	0.999146	MODEM / Modem (Modem-6)	MODEM / Modem (Modem-6)
7	0.999146	0.999146	0.999146	MODEM / Modem (Modem-7)	MODEM / Modem (Modem-7)
8	0.999146	0.999146	0.999146	MODEM / Modem (Modem-8)	MODEM / Modem (Modem-8)
9	0.999146	0.999146	0.999146	MODEM / Modem (Modem-9)	MODEM / Modem (Modem-9)
10	0.999146	0.999146	0.999146	MODEM / Modem (Modem-10)	MODEM / Modem (Modem-10)

Cut Set Analysis



RMA Analysis of GSDO Subsystems

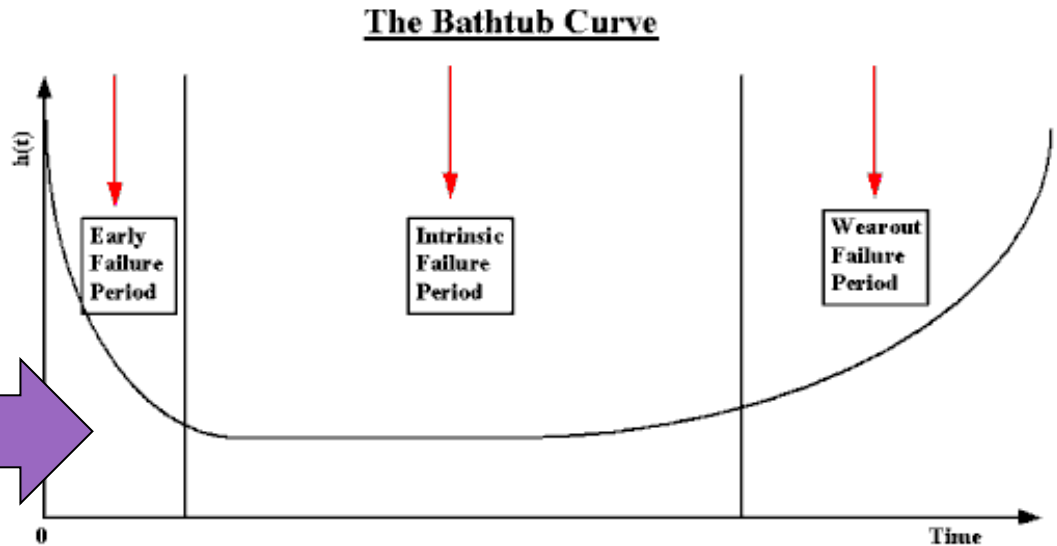
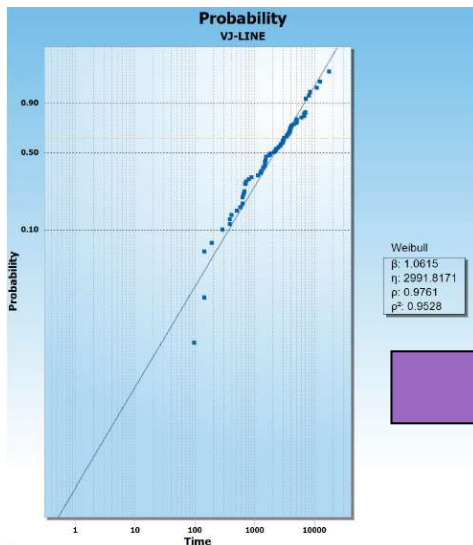
- Example of component data using COTS software:
PTC Windchill Quality Solutions (WQS)

The screenshot displays the PTC Windchill Quality Solutions (WQS) software interface. The top window shows a 'Library Browser' with a search for 'NPRD-43812' and a list of results. The middle window shows a 'System Tree Browser' with a tree view of components. The bottom window shows a 'Parts Table' with columns for Name, Part Number, Part Classification, Category, Subcategory, System Tree Identifier, Reference Designator, Quantity, Calculation Model, Failure Rate, and Tagged. An arrow points from the 'System Tree Browser' to the 'Parts Table'.

Item Name	Part Number	Manufacturer (if known)	MTBF (hrs)	MTBF Source	MTTR (hrs)	MTTR Source
Position Encoder			95,589	NPRD-43920 (NU to GF)	20	Engineering Estimate
Retract Control Valve			147,531	PTC WQS Calculation	5	Engineering Estimate
Pressure Transducer			154,094	NPRD-90101 (NU to GB)	5	Engineering Estimate
Pilot Control Valve			154,094	NPRD-93700 (NU to GB)	5	Engineering Estimate
Motor Controller	KHB12801	Kelly Controls	162,855	NPRD-37121 (AUF to GB)	6	Engineering Estimate
Solenoid Control Valve w/ Actuator			185,250	NPRD-94795 (GF to GB)	5	Engineering Estimate
Switch, Actuator	0HB512		210,396	NPRD-10520 (AUG to GB)	5	Engineering Estimate
Slow Extend/Retract Valve			251,683	PTC WQS Calculation	5	Engineering Estimate
Double Solenoid Valve			271,402	NPRD-94781 (GM to GB)	5	Engineering Estimate
Hydraulic Valve w/ Actuator			294,516	NPRD-94761 (AUF to GB)	5	Engineering Estimate
Circuit Breaker	1489-A1CXXX	Allen-Bradley	404,800	NPRD-2083 (GM to GB)	3.5	PTC WQS Estimate
Retract Valve			462,170	NPRD-94667 (NU to GB)	4.5	Engineering Estimate
Speed Control Valve			462,283	NPRD-93052 (NU to GB)	5	Engineering Estimate

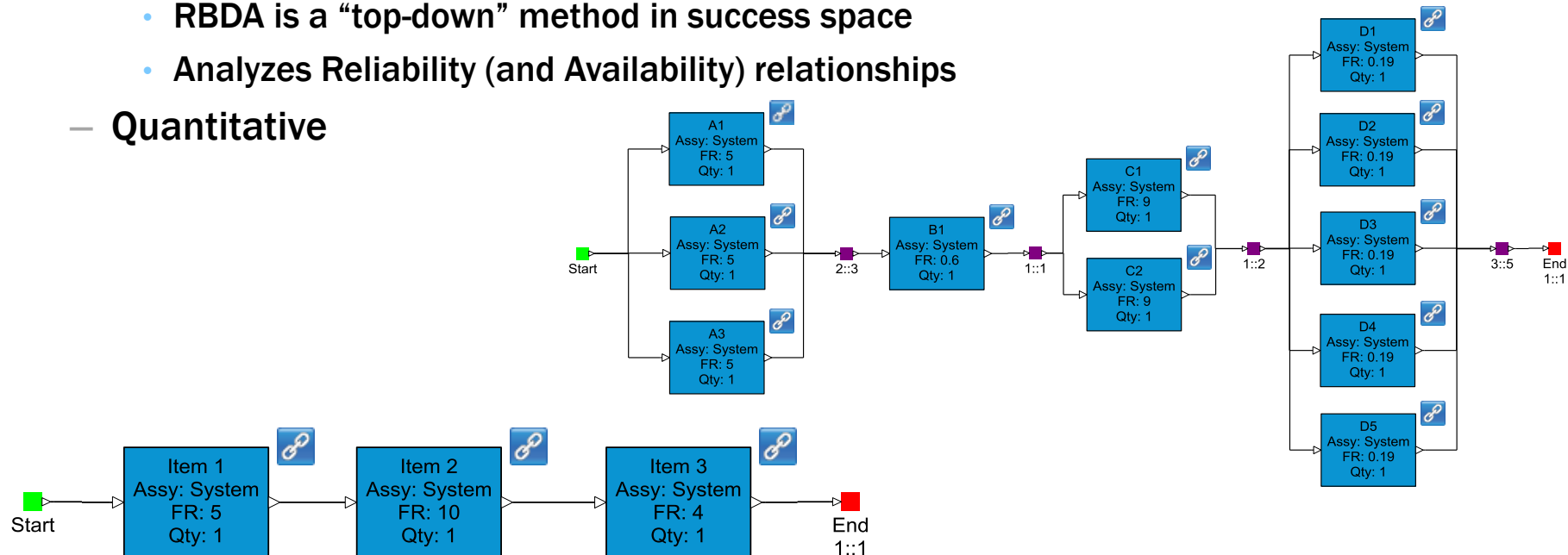
RMA Analysis of GSDO Subsystems

- Analysis of components will sometimes include Weibull analysis to attempt to determine what type of failures are experienced
 - Used for similar components
 - Used for heritage subsystems to characterize failure types seen:
 - Early failures (burn-in)
 - Useful Life (random failures)
 - Wearout



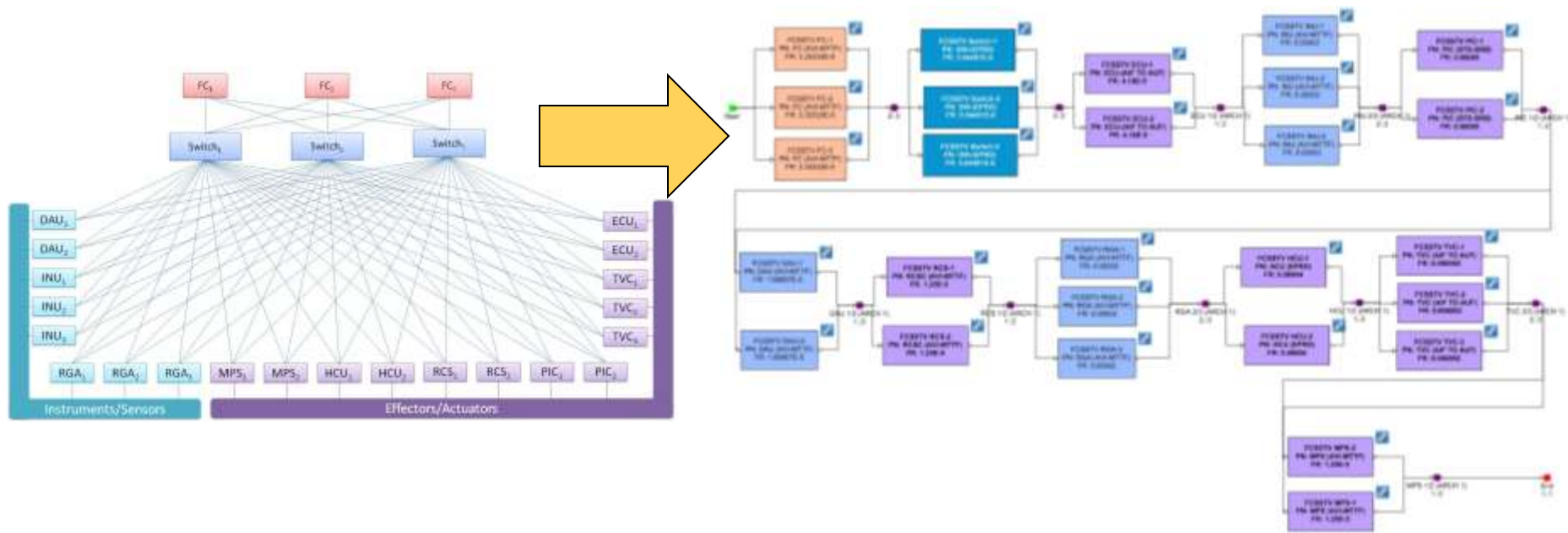
RMA Analysis of GSDO Subsystems

- Reliability Block Diagram (RBD) Analysis (RBDA):
 - Predicts reliability (uptime), maintainability (downtime), and availability (mission readiness being a function of uptime and downtime)
 - The RBDA method is used to estimate and analyze the reliability and availability for the systems containing at least two or more elements
 - RBDA is a “top-down” method in success space
 - Analyzes Reliability (and Availability) relationships
 - Quantitative



RMA Analysis of GSDO Subsystems

- RMA Team converts each drawing (mechanical and electrical) into a Reliability Block Diagram (RBD)
 - Verify accuracy and understanding of the components and their connections with the design team



RMA Analysis of GSDO Subsystems

- RMA team determines the RMA of the subsystem by using both analytical and Monte-Carlo simulation calculations with at least 1,000,000 iterations.
 - Confidence Level set at 95%
- Compare results to requirement

RMA Requirements

Reliability (for 24 hrs)	Maintainability (hrs)	Availability (A_{inh})
0.99900	48	0.998017

Simulation Results

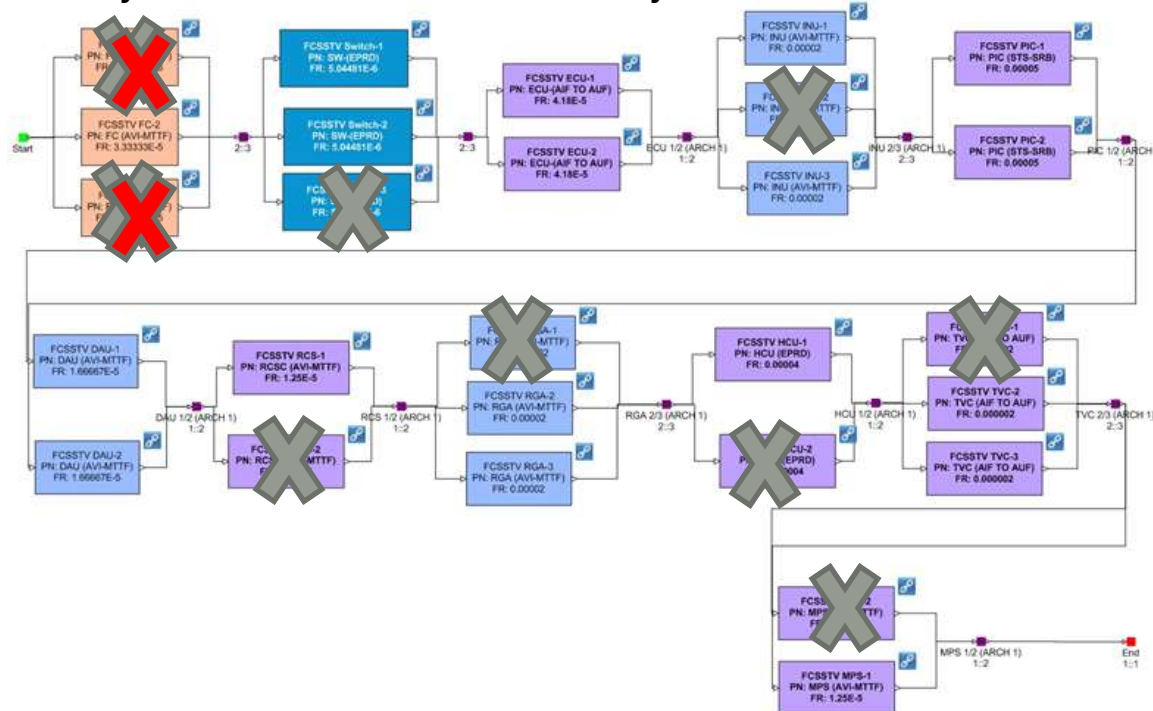
Reliability (for 24 hrs)	Maintainability (hrs)	Availability (A_{inh})
0.998448	12.59	0.999529

- Perform sensitivity analysis to verify consistency in simulations
 - Different random number seeds for Monte-Carlo simulations

Random Seed	Reliability			Failures per Million	MTTR (hrs)	Availability		
	Lower Bound	Point Estimate	Upper Bound			Lower Bound	Point Estimate	Upper Bound
1	0.998564	0.998636	0.998708	54.07	12.59	0.999521	0.999562	0.999603
10	0.998448	0.998523	0.998598	67.10	12.61	0.999439	0.999484	0.999529
100	0.998557	0.998630	0.998703	58.08	12.63	0.999520	0.999561	0.999602

RMA Analysis of GSDO Subsystems

- RMA Team performs Cut Set Analysis (CSA)
 - Set of basic events [failures] where the joint occurrence of these basic events results in the failure of the system.
 - Minimal cut set is a set that “cannot be reduced without losing its status as a cut set”
 - Provides clear indication of where most likely failure paths would be depending on the accuracy of the RBD and the accuracy of the failure data of the components

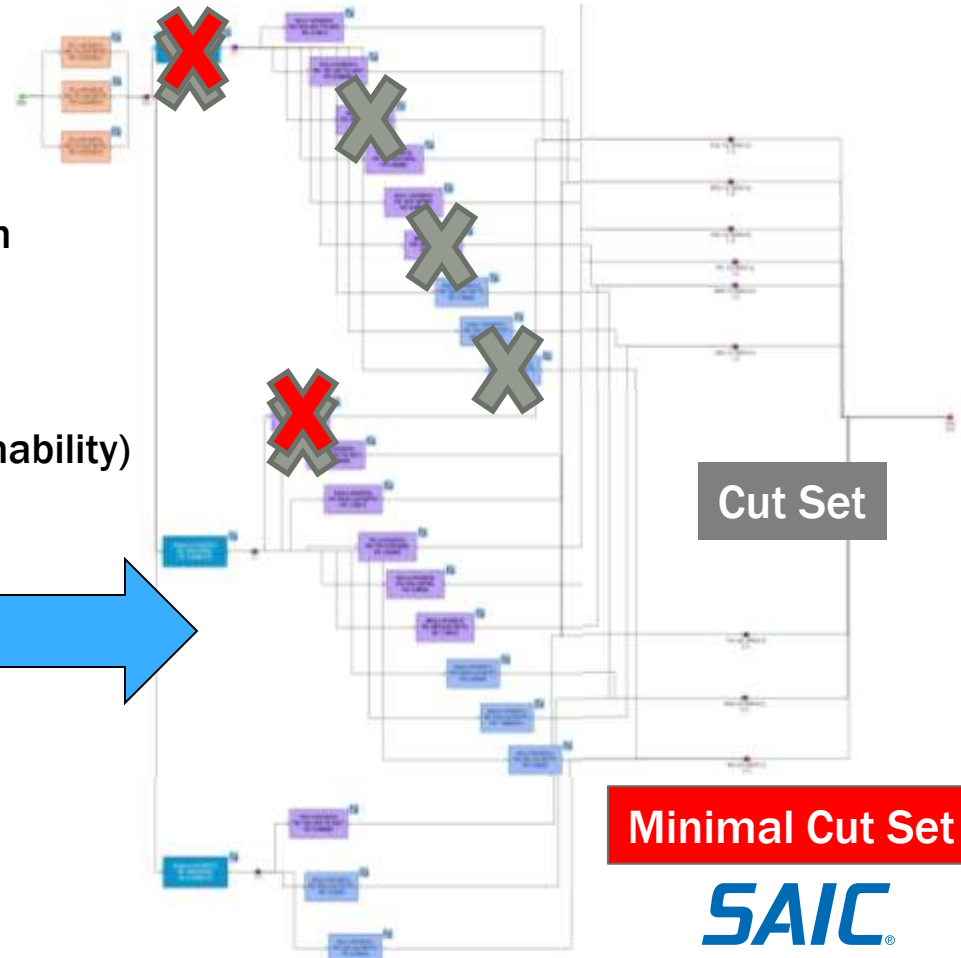
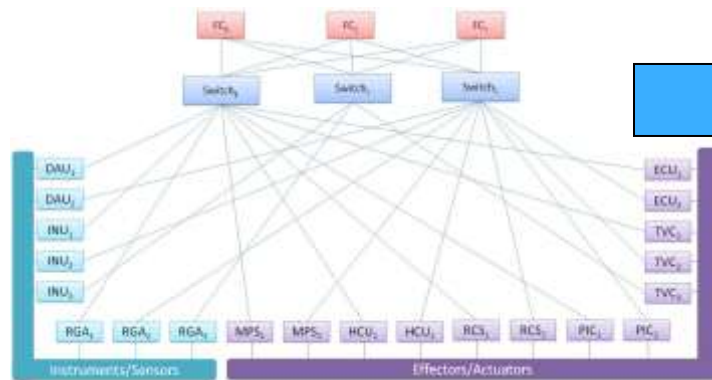


Cut Set

Minimal Cut Set

RMA Analysis of GSDO Subsystems

- When a small number of failure paths make such large contributions to subsystem unavailability, isolating the key failure paths becomes obvious
- This enables the design team to focus on either:
 - Improving the design to correct the high failure nodes (improving reliability), or
 - Ensuring that the component is able to be repaired to an operational state as quickly as possible (improving maintainability)



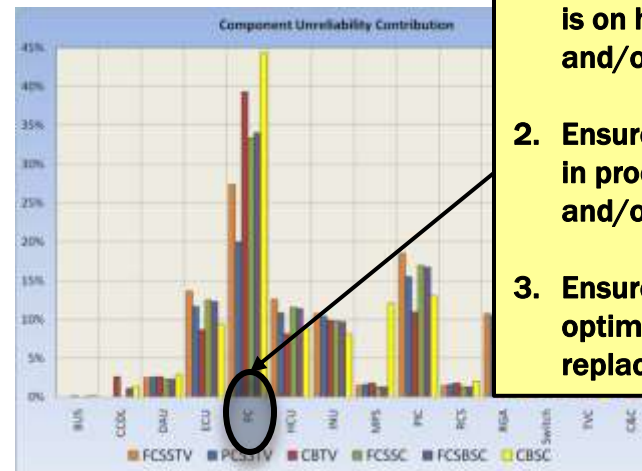
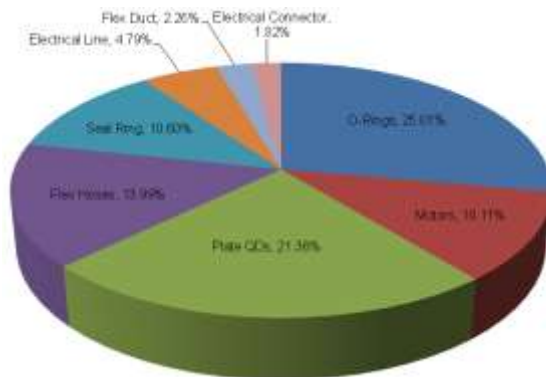
RMA Analysis of GSDO Subsystems

- Example of Cut Set Data

CUM UNAVAIL %	UNAVAIL %	UNAVAIL	Component Failure	Component Failure
5.92%	5.92%	0.000146	ICPSU Position Encoder 1	
11.83%	5.92%	0.000146	ICPSU Position Encoder 3	
13.13%	1.30%	3.22E-05	4000 PSI Hydraulic Supply Pressure Xducer (36583MT-1)	
14.22%	1.08%	2.68E-05	2200 PSI GN2 Supply Valve (36583A12)	
15.17%	0.95%	2.36E-05	Fully Extend Switch (36596)	
15.97%	0.80%	1.97E-05	Slow Extend/Retrack Valve (36583A9)	
16.67%	0.70%	1.72742E-05	CB (GSP to RIO) 50A - Side A	CB (GSP to RIO) 50A - Side B
17.37%	0.70%	1.72742E-05	CB (GSP to RIO) 50A - Side A	Circuit Breaker (CB) 2A - Side B
18.07%	0.70%	1.72742E-05	CB (GSP to RIO) 50A - Side A	Circuit Breaker (CB) to TB - Side B
18.77%	0.70%	1.72742E-05	CB (GSP to RIO) 50A - Side A	Circuit Breaker to Chassis - Side B
19.47%	0.70%	1.72742E-05	CB (GSP to RIO) 50A - Side A	Circuit Breaker to Ind & Enable - Side B
20.17%	0.70%	1.72742E-05	Circuit Breaker (CB) 2A - Side A	CB (GSP to RIO) 50A - Side B
20.87%	0.70%	1.72742E-05	Circuit Breaker (CB) 2A - Side A	Circuit Breaker (CB) 2A - Side B

RMA Analysis of GSDO Subsystems

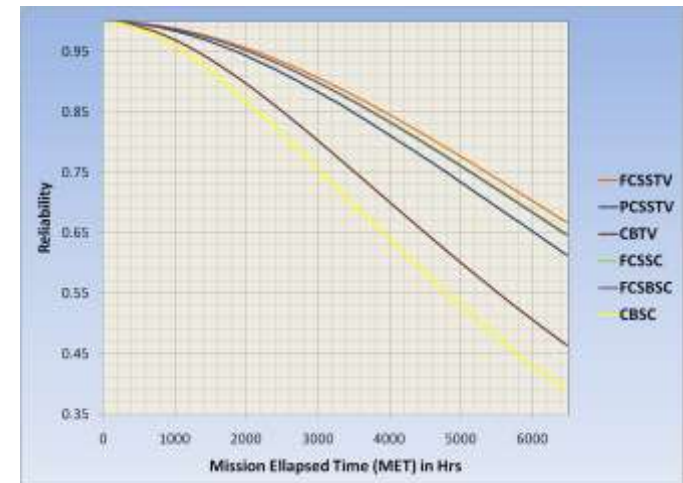
- GSDO RMA Team performs Importance Measure Analysis (IMA)
 - Assesses the importance of the components in the subsystem or the sensitivity of the subsystem RMA to changes in the components' failure rates
 - Quantify the criticality of a particular component within a system design.
 - Used as tool for identifying system weakness, and to prioritize RMA improvement activities
 - Change in the failure rates of the components (or adding redundancy to account for the high failure rate) with the highest importance measure percent contribution will have the most significant effect on increasing subsystem reliability
- This unique method described in paper written by RMA team, entitled, “*Comparison Modeling of System Reliability for Future NASA projects*” and presented at International Reliability and Maintainability Symposium (RAMS) in January 2012



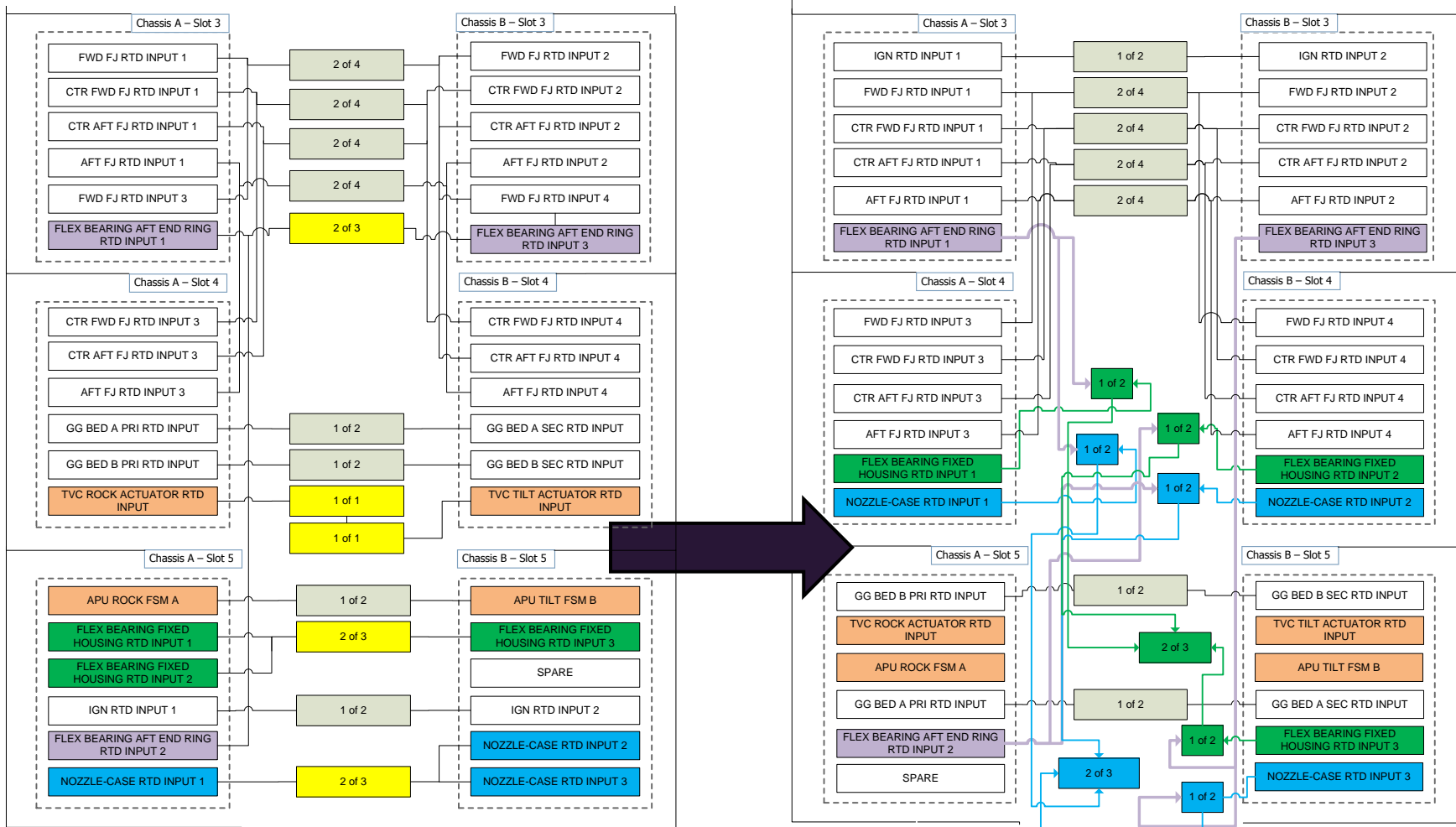
1. Ensure this component/LRU is on hand in order to repair and/or replace when failed.
2. Ensure personnel are trained in procedures for repair and/or replace.
3. Ensure procedures are optimized for repair and/or replace.

RMA Analysis of GSDO Subsystems

- GSDO RMA Team reports results and recommendations in Subsystem RMA reports
 - Example recommendations for RMA improvement:
 - Have redundant components on separate busses
 - Improved availability by an order of magnitude (0.995 to 0.9994)
 - Move control and monitoring to different Programmable Logic Controller (PLC)
 - Had redundant monitoring on same PLC (*see next page*)
 - Improved availability by three orders of magnitude (0.9993 to 0.999999)
 - Example recommendations for trades:
 - Tertiary power system provides little to no improvement in availability (0.999995 to 0.999996); does not justify additional weight, space, and cost
 - Avionics architectures: triplex voter improves availability, however, self-checking pair does not



RMA Analysis of GSDO Subsystems

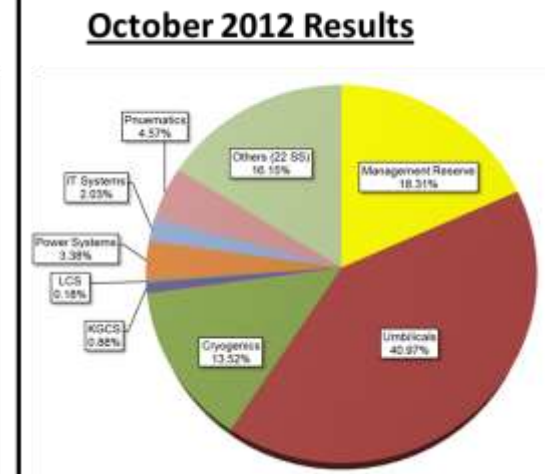
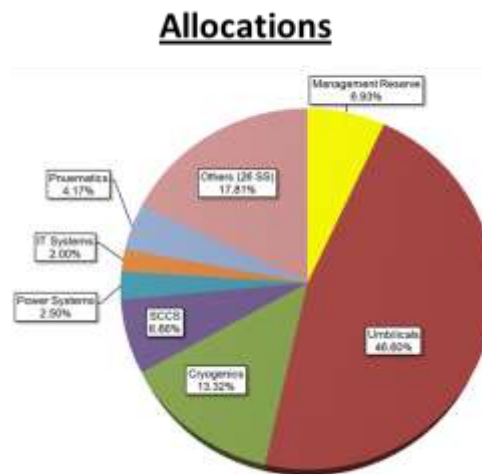
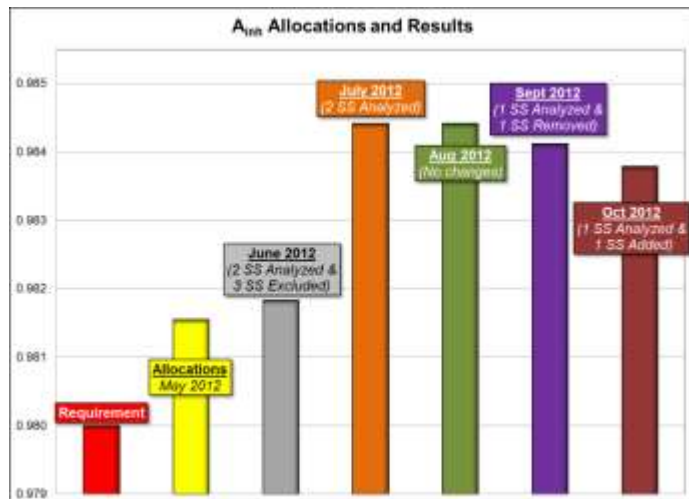


$R(10) = 0.999300$

$R(10) = 0.999999$

RMA Analysis of GSDO Subsystems

- Effectively monitoring and tracking RMA analysis results for management
 - Management informed of risk to achieving requirements almost immediately
- RMA tracking & reporting methodology effective and efficient in communicating recommendations for RMA improvements
 - Can quantify RMA improvements versus cost, scheduling, weight, space impacts

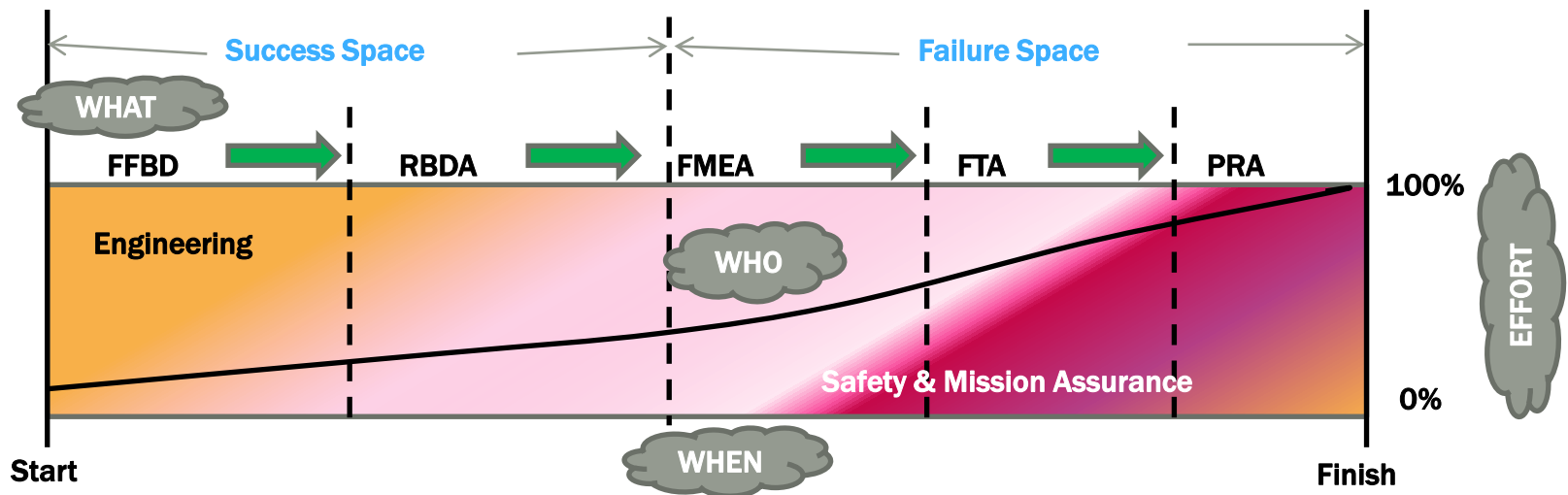


RMA Analysis of GSDO Subsystems - Summary

- **GSDO requirements allocated to subsystems**
 - Inherent Launch Availability is allocated to those subsystems in the launch countdown window
 - Operational Availability is allocated to those subsystems not included in the Inherent Launch Availability allocation, but needed in the event of a launch scrub
- **GSDO RMA team performing RMA analysis of subsystem designs and upgrades, as well as heritage subsystems**
 - Analysis of heritage subsystems includes Weibull analysis to attempt to determine what type of failures experienced: Early failures (burn-in), Useful Life (random failures), Wearout
- **GSDO is tracking and reporting RMA analysis results of ground hardware and software components**
- **FTA, FMEA, etc are performed as part of the design development cycle to drive out subsystem hazards and single failure points**

Other RMA Analyses

- Failure Modes & Effects Analysis (FMEA)
- Fault Tree Analysis (FTA)
- Probabilistic Risk Assessment (PRA)
- Historical Component Failure Rate Determination
- Component Burn-in and Test Time Requirements



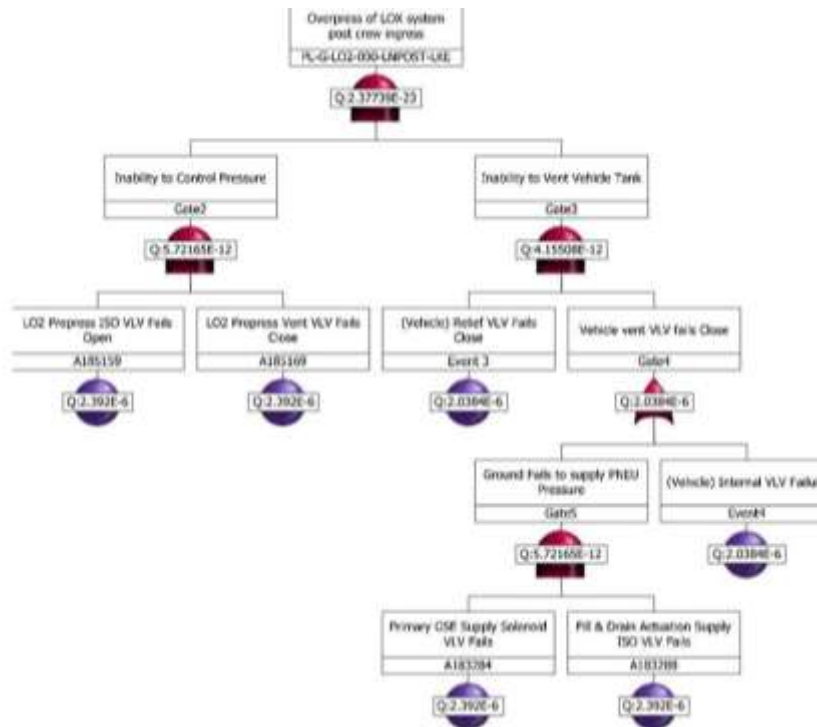
Failure Modes and Effects Analysis (FMEA)

- Inductive (bottom-up) method where a table that describes the way or modes in which each system component can fail and assess the consequences of each of these failures is generated
- Determines hardware criticality
- Identifies failure modes that do not meet applicable Program reliability requirements
- Identifies the potential for single point failures
- Identifies areas where the design does not meet the failure tolerance requirements
- Changed from qualitative to quantitative by assigning values to:
 1. Probability of the failure occurring,
 2. Severity of the effect of the failure on the operation of the systems,
 3. Probability that the system controls will detect and eliminate the failure before the design is complete.
 - The product of all three values is the risk priority number (rpn)

Rating	Description	Criteria
1	Very Low or None	Minor nuisance
2	Low or Minor	Product operable at reduced performance
3	Moderate or Significant	Gradual performance degradation
4	High	Loss of function
5	Very High or Catastrophic	Safety-related catastrophic failures

Fault Tree Analysis (FTA)

- Deductive (top-down) method that generates a symbolic logic model that traces and analyzes the failure paths from a predetermined, undesirable condition or event (called the top event) of a system to the failures or faults
- Can be qualitative or quantitative – *we do quantitative*
- FTA is an event-oriented analysis in contrast to the RBD, which is a structural-oriented analysis

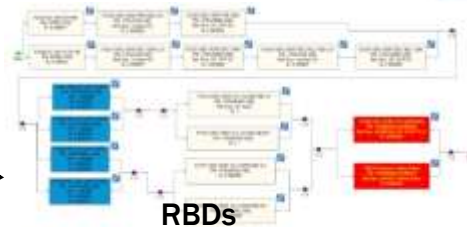
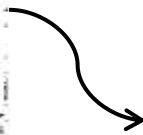
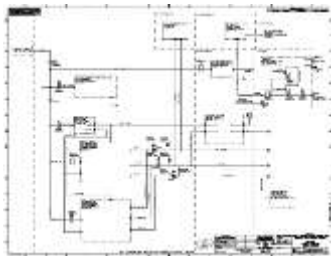


Probabilistic Risk Assessment (PRA)

- Systematic and comprehensive methodology to evaluate risks associated with a complex system
- Risk in PRA is defined as scenarios, associated frequencies, and associated consequences
 - Risk management involves prevention of adverse scenarios and promotion of favorable scenarios
 - NASA uses Risk metrics of probability of loss of vehicle, mission failure, etc
- Goal is to describe how the system and its elements respond to an undesired initiating event, such as lightening or fire
- Quantitative
 - Magnitude of the possible adverse consequence
 - Probability of the occurrence of each consequence
- Include:
 - Human Reliability Analysis (HRA)
 - Common-Cause-Failure Analysis (CCF)

Probabilistic Risk Assessment (PRA)

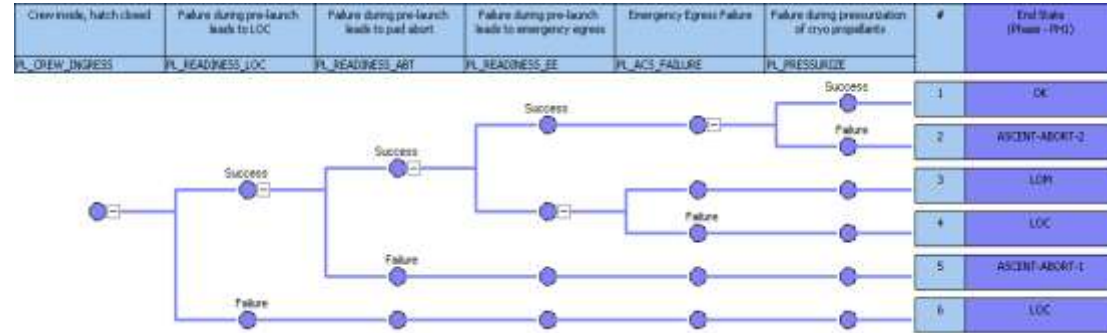
Drawings



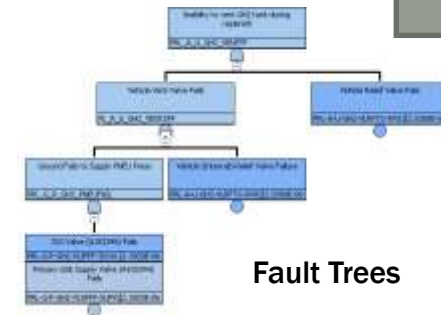
RBDs



Hazard Reports

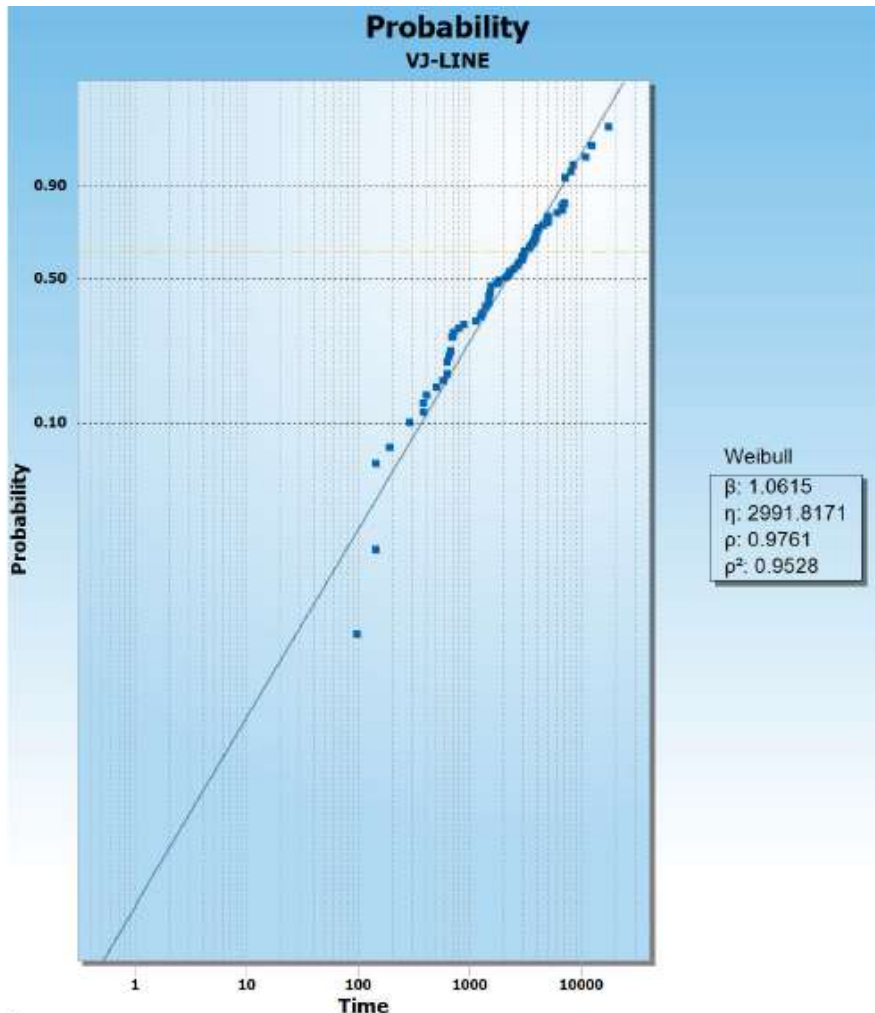


Event Tree



Fault Trees

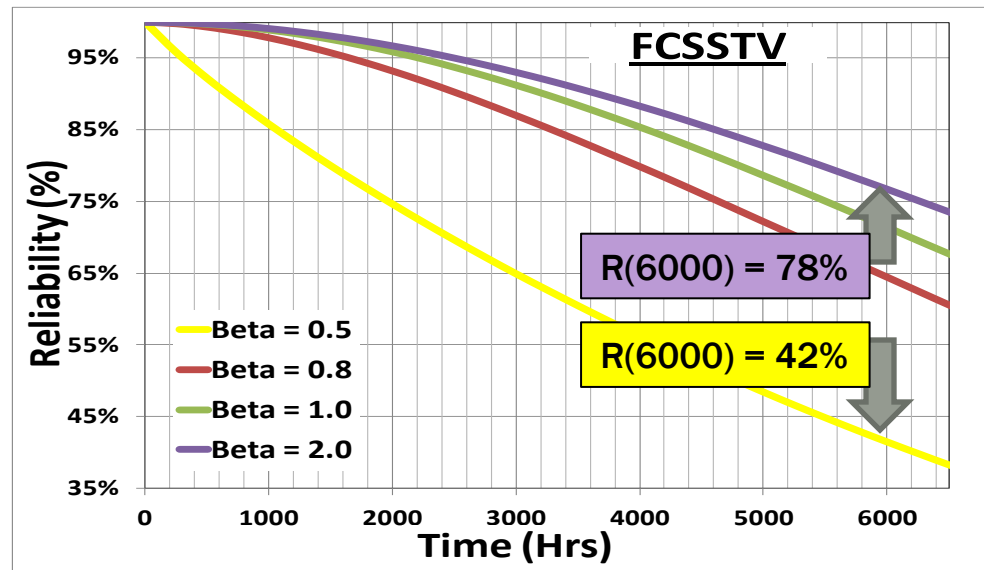
Historical Component Failure Rate Determination



- Using 442 PRACA records:
 - Input into Weibull Analysis
 - Results:
 - It is in its useful life cycle, with random failures
 - $\beta=1.0615$
 - MTBF = 2991 hrs
 - Assumptions
 - Repair Time: 223 hrs
 - Inspection Time: 8 hrs
 - Maintainability
 - Maximum Availability = 87%
 - Inspection Time = 220 hrs

Component Burn-in & Test Time Requirements

- RMA Analysis can determine product testing parameters
 - Reliability life testing can quantify reliability or safety goals
 - Burn-in test times can determine constant failure rates
 - Can determine acceptance test parameters
- The Weibull shape parameter (β) corresponds to the different failure modes for components
 - Infant mortality when β is less than 1
 - Random defects when β is equal to 1
 - Wear-out when β is greater than 1
- The results of system reliability analysis can be misleading if components are not properly up-screened (burned-in) or used under a certain bias condition where different failure modes may occur



Why Have RMA Analysis in Design Process?

- RMA Analysis provides quantitative results, which can be used to justify component replacement, system upgrades, cost effectiveness of “abandon in place” concepts for systems, etc
- GSDO RMA process allows for verification and traceability of RMA requirements
- GSDO RMA Analysis encompasses entire design life cycle
 - *RBDA* – *FTA*
 - *FMEA* – *PRA*
- RMA Analysis can be used to optimize timeline and launch availability results
 - *Provide MTBF, failure distribution, MTTR, and repair probability to Ground System hardware and software*
- RMA Analysis can be used to optimize Logistics considerations
 - *Spare parts need* – *Preventative Maintenance requirements*
 - *Logistic Facility space* – *Maintenance Personnel Requirements*

GSDO RMA Analysis Papers

- **GSDO RMA Team Papers Published:**
 - *“On Component Reliability and System Reliability for Space Missions,”* IEEE International Reliability Physics Symposium (IRPS) 2012, Anaheim, CA, 2012
 - *“Comparison Modeling of System Reliability for Future NASA Projects,”* Reliability, Availability, and Maintainability Symposium (RAMS) 2012 Conference, Reno, NV, 2012.
 - *“Constellation Ground Systems Launch Availability Analysis: Enhancing Highly Reliable Launch Systems Design,”* American Institute of Aeronautics and Astronautics (AIAA) 2010-2180, SpaceOps 2010 Conference, Huntsville, Alabama, 2010.
- **Future Papers for Reliability and Maintainability Symposium (RAMS) 2013 (January 2013 in Orlando, FL):**
 - *“Allocating Reliability & Maintainability Goals to NASA Ground Systems”*
 - Paper described GSDO RMA Allocation process for GSDO
 - *“Determining Component Probability from Problem Report Data Used in Ground Systems for Manned Space Flight”*
 - Describes process of capturing qualitative PRACA failure data for use to determine quantitative component reliabilities

Thank You

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Acronym & Abbreviation List

A_i	Inherent Availability
A_o	Operational Availability
ASQ	American Society for Quality
CRE	Certified Reliability Engineer
CSA	Cut Set Analysis
CxP	Constellation Program
DoD	Department of Defense
FFBD	Functional Flow Block Diagram
FMEA	Failure Mode & Effects Analysis
FTA	Fault Tree Analysis
GSDO	Ground Systems Development and Operations
IMA	Importance Measure Analysis
KSC	Kennedy Space Center

KSC-NE	KSC Design Engineering
MPCV	Multi-Purpose Crewed Vehicle
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
NASA	National Aeronautics and Space Administration
PLC	Programmable Logic Controller
PRA	Probabilistic Risk Assessment
PTC	Parametric Technology Corporation
R&M	Reliability & Maintainability
RAMS	Reliability and Maintainability Symposium
RBD	Reliability Block Diagram
RBDA	Reliability Block Diagram Analysis
RMA	Reliability, Maintainability, and Availability

Acronym & Abbreviation List

SAIC	Science Applications International Corporation
SLS	Space Launch System
SSP	Space Shuttle Program
WQS	Windchill Quality Solutions
Wx	Weather